# Directed Design of Experiments (DOE) for Determining Probability of Detection (POD) Capability of NDE Systems (DOEPOD)

Ed Generazio

Agency NDE Specialist
Research and Technology Directorate
National Aeronautics and Space Administration
Langley Research Center, Hampton, VA

NDE Program Manager
Safety and Mission Assurance Office
National Aeronautics and Space Administration Headquarters, Washington, DC

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Ward D. Rummel, D&W Enterprises, for his unwavering support, encouragement, recommendations, and testing of DOEPOD software.

# OUTLINE

- Binomial Distribution
- Process for determining observed probability of hit (POH) and associated confidence limits
- DOEPOD Software
- DOEPOD Analysis
- Future work

# Background

*"I'm too much of a knucklehead to know this stuff"*

*"Oh boy, confidence limits. I hate these."*

*"They don't use 90/50 they use 90/95."*

*"I should have used 90/50"*

*"I defer my answer to the statistician"*

*"I'm not a statistician."*

*"90/50 POD means that there is a 50% chance that the true POD is greater than 90% at that flaw size?" Responses: "No.", and "Yes." , rest of world gives blank stares.*

*"Confusion over 'common definitions' continues to be an issue…"*

*"We have been using 29 out of 29 clandestinely for years"*

# Background (continued)

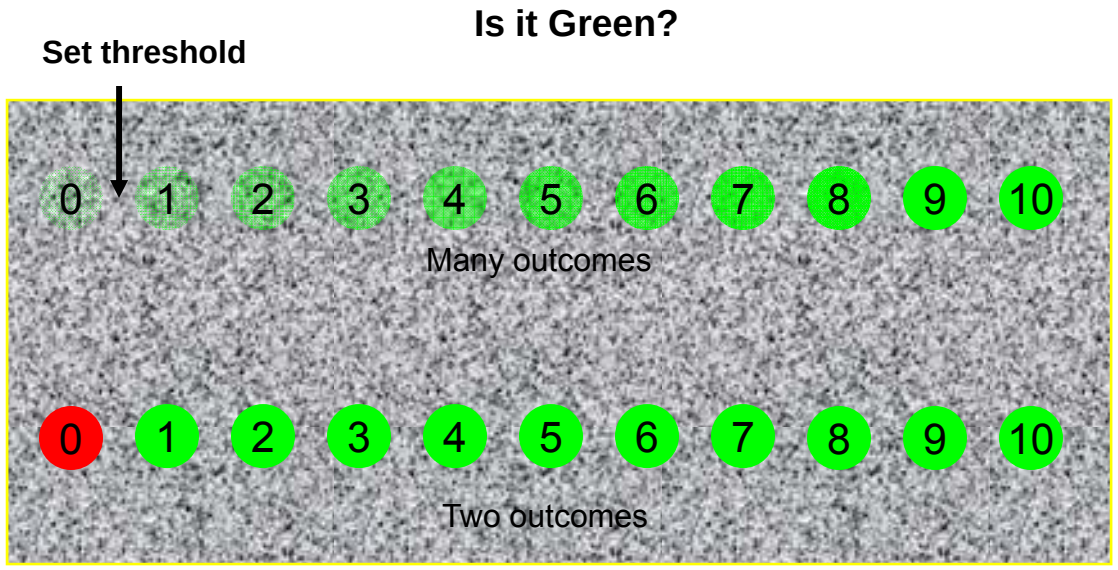
- A core issue here is that the NDE personnel, nationwide, have differentt levels of understanding of statistics, and have delegated basic NDE POD statistical analysis to the statisticians.
- This environment created a divergence in the interrelationship between the physics of the inspection procedure and the POD statistics.
- NDE community should not blindly accept statistical results, but rather challenge the statistical results.
- When NDE personnel defer explanations  on statistical confidence bounds to others, it's like saying "I don't understand the error bars of my data".
- This is not a good position.
- We all need to learn and to speak the language of the other.
- This is the authors attempt to begin to bridge this gap.

# Using The Binomial Distribution

The binomial distribution describes the behavior of a count variable X if the following conditions apply:

- The number of observations N is fixed.
- Each observation is independent.
- Each observation represents one of two outcomes ("success" or "failure").
- Use “green” or “red” to represent “Hit” or “Miss”, respectively.
- The probability of ”Hit" (POH) is the same for each outcome.

If these conditions are met, then X has a binomial distribution.



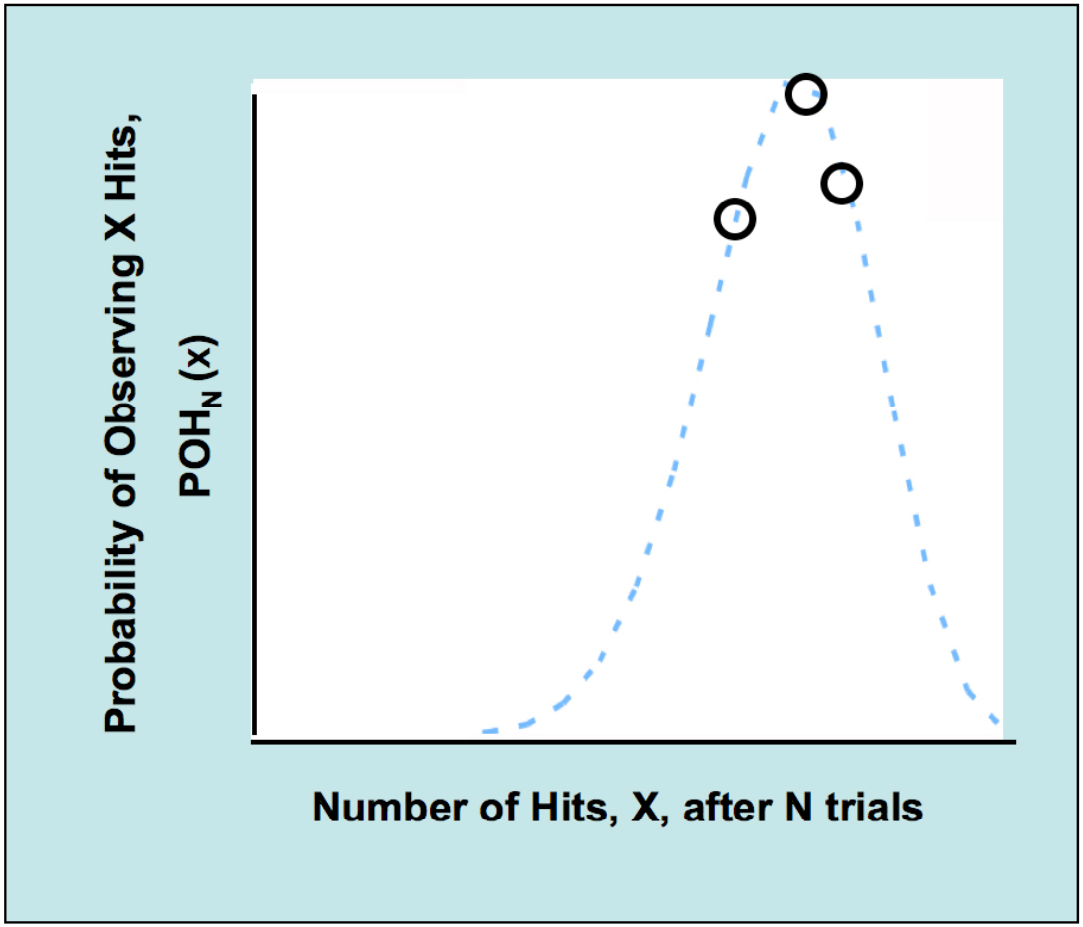

**ANALOGY**

**Various shades (amplitudes) may be due to crack size, signal amplitude, etc.**

**Hit/Miss**

**By setting a threshold only two outcomes (Hit/Miss) observations are obtained.**

# Using The Binomial Distribution (continued)




O = Example values of POH as observed during a test.

**Use binomial distribution for now.**

**Other distributions may be used if they can be demonstrated to be better.**

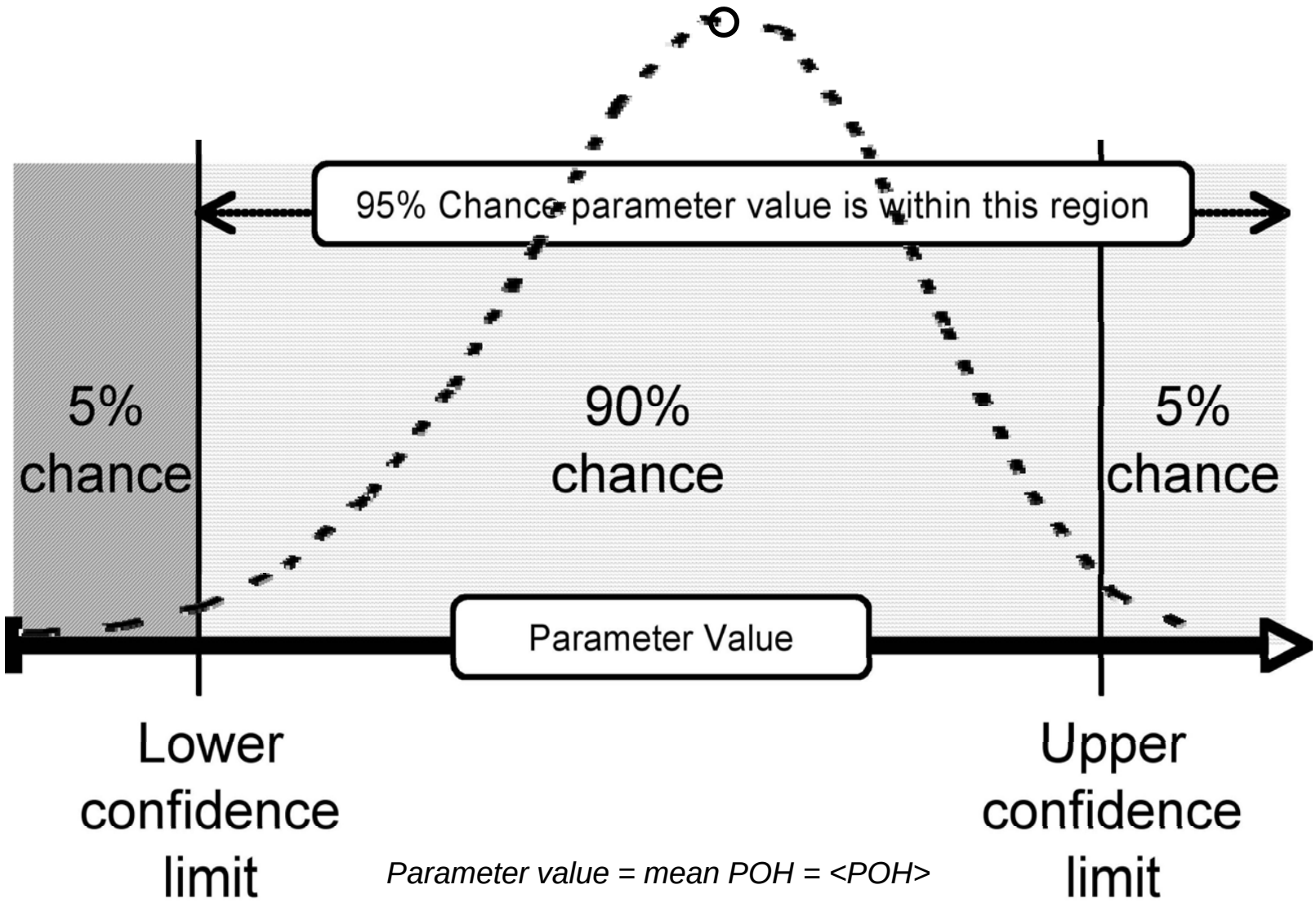
# Probability of Hit (POH) Example

- Start with 61 flaws in the group.
- Each flaw has with the same probability of being observed as a Hit.
- Make 61 observations.
- If 59 Hits are observed, then the Probability of Hit is POH = 59/61 = 0.97 (the observed frequency)
- This is an estimated POH since the true POH can only be approached by making an "infinite" amount of observations.
- Now that the Probability of Hit is measured, what is the confidence in that value?
- This is somewhat analogous to asking what are the error bars or uncertainty in measurements.
- *Confidence level is the measure of probability associated with a confidence interval expressing the probability of truth of a statement that the interval will include the parameter value.*
- For NDE applications, the confidence bound of interest for Probability of Hit is the lower confidence bound.

# 95% Confidence Level Example

**If we achieve a lower confidence limit (bound, value) = 0.90 , then**

**"There is a 95% chance that the true POH is greater than 90% for that flaw size"**




*Parameter value = mean POH = <POH>*

# Confidence Level Example (continued)

With X = 59 Hits after N = 61 trials, yielding 59/61 = 0.97 POH (the observed frequency), the lower confidence bound, $P_l$ , may be obtained from*

$$P_l = \frac{X}{X + (N - X + 1) F_\alpha(f_1, f_2)} \quad , \quad F_\alpha(f_1, f_2) = 2.25 \left\{ \begin{array}{l} f_1 = 2(N - X + 1) = 6 \\ f_2 = 2X = 118 \end{array} \right\}$$

$$P_l = 0.9$$

$\alpha$ is, a priori, the confidence level, 95%, that we are requiring

$F_\alpha(f_1, f_2)$ is obtained from the F-distribution statistical table

**Note that the POH does NOT change if the confidence level is changed**

**Introduction to Statistical Analysis", W. J. Dixon and F. J. Massey Jr., 3rd Edition, 1969, "Statistical Theory with Engineering Applications", A. Hald, 1952, and "Recommended Practice for Demonstration of Nondestructive (NDE) Reliability on Aircraft Production Parts", Ward D. Rummel, Materials Evaluation, vol 40, August 1982*

# 95% Confidence Level Example (continued)

$$P_l = 0.9$$

**There is an 95% chance that the true POH is greater than 0.9 at that flaw size**

**Or**

**There is a 95% chance that the inspection system reliability is greater than 0.9 at that flaw size**

**Or**

**90/95 POD at that flaw size**

# Directed Design of Experiments for Validating Probability of Detection of Inspection Systems (DOEPOD)

## DOEPOD Concepts

- Not all flaws are created equally; never identical; but they may be grouped into classes by size, length, depth, etc. These classes have ranges or widths.

- DOEPOD is a confidence value driven approach.

- DOEPOD uses moving class width and variable class width optimization to identify the best lower confidence bound. Class widths start at 0.001” and increase.

- DOEPOD uses real initial flaw, simulated, or completed inspection data sets. Guidelines are in the manual. (Smallest number of samples is 5).

# Grouping of Flawed Specimens

- Flaws may be grouped into classes by size, length, depth, etc. The grouping may be any class width, e.g., 0.001”, 0.036”, 0.100”, etc.

- If there are sufficient number of flaws, then a moving “class width” may be used to dynamically group adjacent flaws into classes with widths (classwidths).
  - E.g., all flaws in the range 0.050” - 0.150” may be in a group, with the largest flaw being the identifier for the group.

    - Class width here is 0.100”

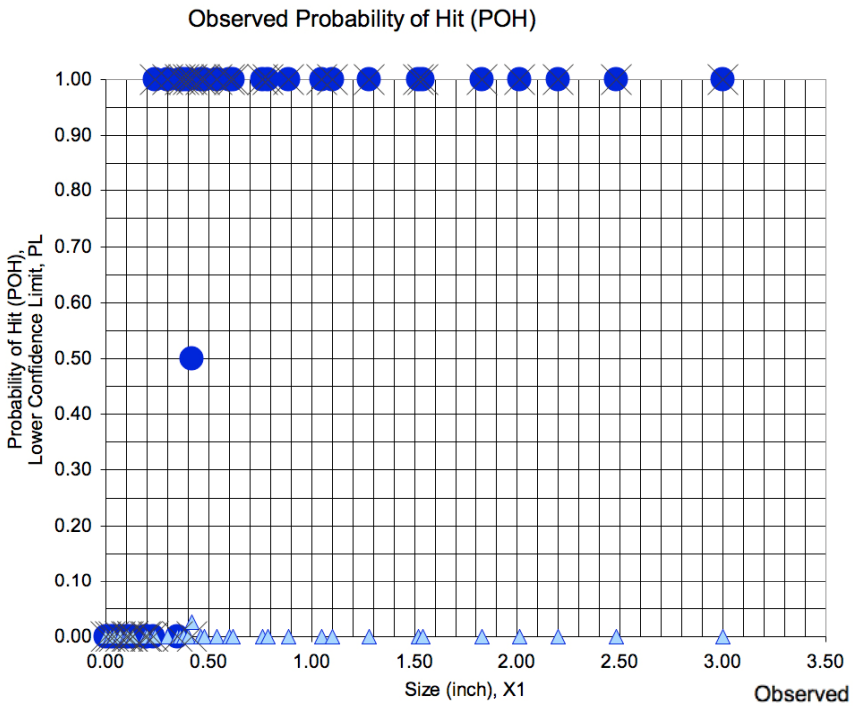
    - The next group may contain the range 0.049” - 0.149” ; the class width is moving from largest to smallest flaws.

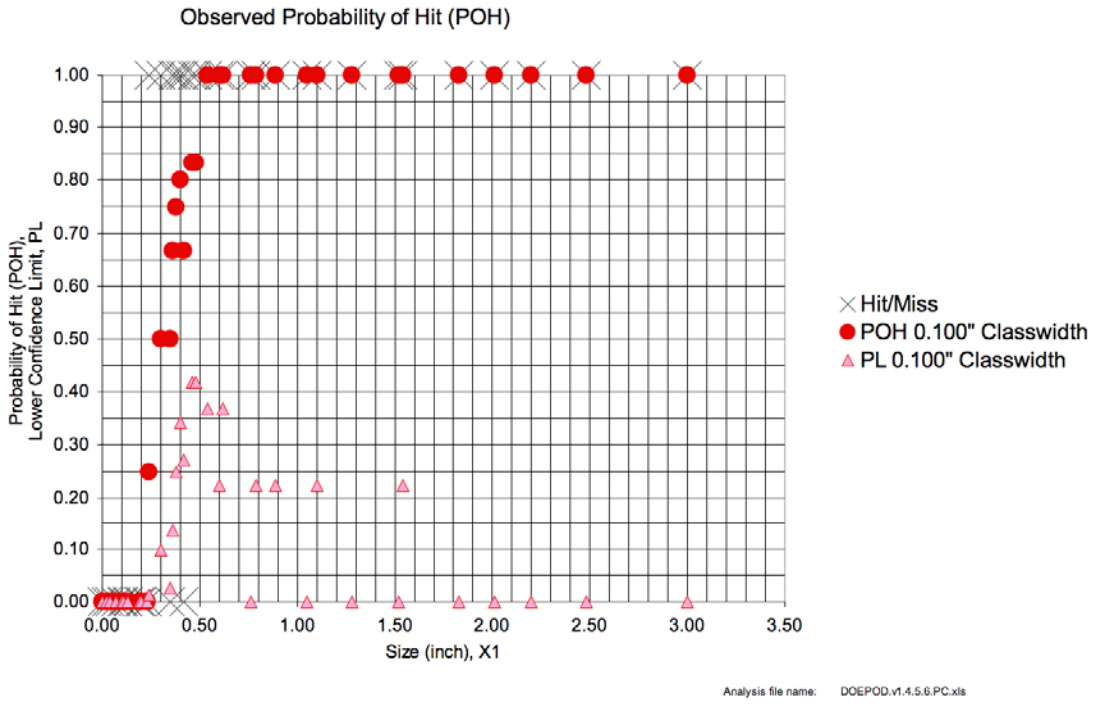
- POH needs to be determined for each flaw size grouping (number of flaws in each group is not necessarily the same)

- Confidence bounds need to be determined for each flaw size grouping (both X and N vary for each group)

**What is the optimum class width?**

# Effect of Grouping of Flawed Specimens




*Important: When grouping flaws, the observed POH and confidence bound is assigned to the largest flaw in the group*

# DOEPOD

## DOEPOD Concepts (continued)

- Using POH lower confidence bound (value) as driver for directing DOE.

- If 90/95 POD is reached at a then identify locations that need additional vaildation for larger flaw sizes.

- If 90/95 POD is not reached then use best lower confidence value to identify where options are available to reach 90/95 POD.

- Identify CASE of the data set.

- Provide directions, depending on the CASE, on how to modify the DOE to continue to efficiently validate the inspection system.

- Determine false call rate and associated confidence limit[L]

# DOEPOD Parameters

| | |
|---|---|
| **Class length** | **Inspection parameter (length, depth, etc.)** |
| **Hit** | **Flaw is detected** |
| **Miss** | **Flaw is not detected** |
| **Need** | **Add new samples to the existing set in order to reach the number of samples required at the class length** |
| **LCL** | **Lower confidence bound (value) of POH @ 95% confidence** |
| **Opt. $X_{POH}$**<br>**Optimum $X_{POH}$** | **Optimum $X_{POH}$ is identified for non-survey data sets. Optimum $X_{POH}$ is the smallest class length and largest class width at which the minimum $X_{POH}$ = 1 occurs.** Optimum $X_{POH}$ may be more aggressive than optional, $X_{PODopt}$, or $X_{Best\ LCL}$, when the class width is constrained to the companion Optimum $X_{POH}$ class width listed. DOEPOD does not force use of Optimum $X_{POH}$ over $X_{PODopt.}$ or $X_{Best\ LCL}$ Stability has not been demonstrated at Optimum $X_{POH,}$ therefore there is an additional risk that can not be satisfied. |
| **POH** | **Probability of Hit (Number of Hits in Classwidth/Total Number of Trials in Classwidth)** |
| **POD** | **Probability of Detection (the true POD obtained if an infinite number of samples are used)** |
| **Signal Amplitude** | **Scalar amplitude output of NDE inspection system** |
| **Survey Data Sets** | **Survey Data Sets are data sets that have a sparse or disperse collection of samples.** The moving class width optimization has identified this set as having limited applications to moving class width processing. An alternate optimization of $X_{POH}$ is used to provide guidance. |
| **Survey $X_{POH}$** | **Survey $X_{POH}$ is only identified for data sets determined to be Survey Data Sets. Survey $X_{POH}$ is the smallest class length and largest class width at which the minimum $X_{POH}$ = 1 class length occurs.** Survey $X_{POH}$ is the minimum class length at which $X_{POD}$ may be achieved when the class width is constrained to the companion survey class width listed. Survey $X_{POH}$ is utilized in all cases in which it occurs. |

# DOEPOD Parameters (continued)

| | |
|---|---|
| $X_{Best\ LCL}$ | **Class length exhibiting the best LCL. The best class length is determined by increasing the moving class width until a maximum LCL is obtained** |
| $X_i$ | **Class length X at point "i"** |
| $X_L$ | **Largest class length in entire data set** |
| $X_m$ | **Class length near the mid-point between the largest and the smallest class lengths having no misses** |
| $X_{POD}$ | **Class length at which the lower confidence bound (value) is 0.90 or greater (90/95 POD)** |
| $X_{POH=1}$ | **Class length where there are no misses above this class length** |
| $X_{PODopt}$ | **Recommended optional existing smaller class length where $X_{POD}$ may also be achieved if additional sample are added.** |
| $X_S$ | **Smallest class length in data set** |
| UCL | **Upper confidence value of the false call rate @ 95% confidence** |

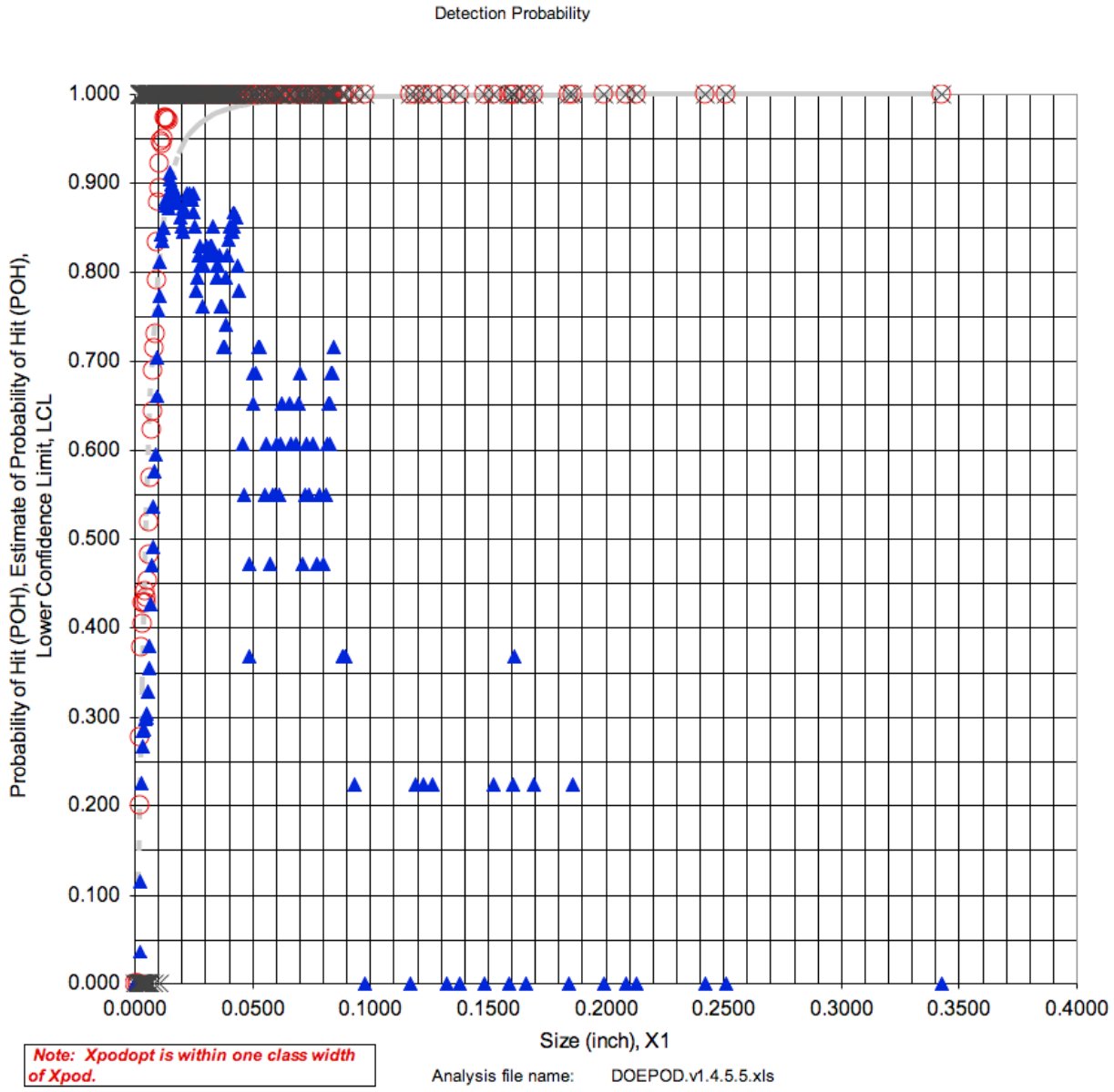
# Case #1 (Best Case)

- 90/95 $X_{POD}$ reached at a class length
- Misses only below $X_{POD}$ (and POH =1 everywhere greater than $X_{POD}$)

***Directed Requirements for Validation of 90/95 $X_{POD}$***

- Need samples at largest class length, $X_L$
- Need samples at mid-class length, $X_m \approx (X_L - X_{POD})/2$
- Option: Adding samples at $X_{podopt}$ may yield a new $X_{POD}$ with a smaller class length.
- If this is a survey data set, then only need to add samples at Survey $X_{POH}$ (if listed)
- Option: The user may add samples at Optimum $X_{POH.}$ The class width for all added samples at any class length is shown along with the Optimum $X_{POH.}$
- The range of validation may be expanded by adding samples at $2X_L$, $4X_L$, $8X_L$, $16X_L$, etc, if the current range of validation is too small.

# Case #1 (Best Case)




| | | |
|---|---|---|
| File Name = | A8002L.Case1.XLS | |
| Data Set Name = | A8002L.Case1(Eci-a-b5 | |
| Date & Time = | 5/11/07 4:26 PM | |
| Xpod 90/95 Reached Anywhere? | REACHED | |
| Classwidth @ 90/95 Xpod = | 0.0040 | inch |
| Classlength @ 90/95 Xpod = | 0.0147 | inch |
| Actual Lower Confidence Value = | 0.9120 | |
| Best LCL = | | |
| Classwidth @ Best LCL = | | inch |
| Classlength @ Best LCL = | | inch |
| a(1) [Alpha] = | 10.34 | |
| a(2) [Beta] = | 1.94 | |
| Chi-Square = | 0.0023 | |

*CASE 1 - 90/95 Xpod is VALIDATED from Xpod to XL when XL and Xm are satisfied. An alternate 90/95 Xpod is available if Xpodpot or Optimum Xpoh (if listed) is also satisfied.*

Survey/Optimum Xpoh = 0.0115 -0.001 inch (need 18 Samples)

NTIAC 90% POD = 0.942 @ 0.010 inch

NTIAC 90/95 POD = 0.952 @ 0.015 inch

False Call Rate = with UCL @ 95% =

| | | |
|---|---|---|
| Largest Classlength , XL = | 0.342 | inch |
| Samples Needed @ XL = | 28 | |
| Classlength Mid-point , Xm = | 0.161 | inch |
| Samples Needed @ Xm = | 26 | |
| Smallest Classlength, Xs = | | inch |
| Samples Needed @ Xs = | | |
| New Smaller Classlength, Xss = | | inch |
| BestLCL Classlength, Xlcl = | | inch |
| Samples Needed @ Xlcl = | | |
| POH Classlength, Xpoh = | | inch |
| Samples Needed @ Xpoh = | | |
| New Largest Classlength , 2XL = | | inch |
| Xm is Near Verification Point = | | inch |
| Opt. POD classlength, Xpodopt = | 0.0145 | inch |
| Samples Needed @Xpodopt = | 29 | |

# Case #2

• 90/95 $X_{POD}$ reached at a class length

• There are misses below $X_{POD}$ and some misses above $X_{POD.}$ This is expected as $X_{POD}$ nears the capability of the inspection system.

• Since misses exist at class lengths $X_i$ above $X_{POD}$ , then these greater lengths need to be validated. (i.e., The POH < 1 at class lengths $X_i$ above $X_{POD}$ point, $X_{POD}$ , so these greater lengths need to be validated.)

## *Directed Requirements*

➢ There are two (2) options that may be used to move this Case #2 toward Case #1

(a) Add samples of class length $X_i$ where POH<1 (TABLE A). Starting from largest class length, $X_i$ , and work toward small class lengths until reaching an acceptable $X_{POD}$ or reaching $X_{POD.}$

(b) Add samples of class length $X_i$ where POH=1 (TABLE B). Accept a larger $X_{POD}$ class length at any of the $X_i$ . This acceptance is valid as long as any existing larger class lengths where POH<1 are shown [via (a) above] to be at 90/95 $X_{POD}$ or greater. Acceptance of a larger $X_{POD}$ is not necessarily the $X_{POD}$ capability for the inspection system.

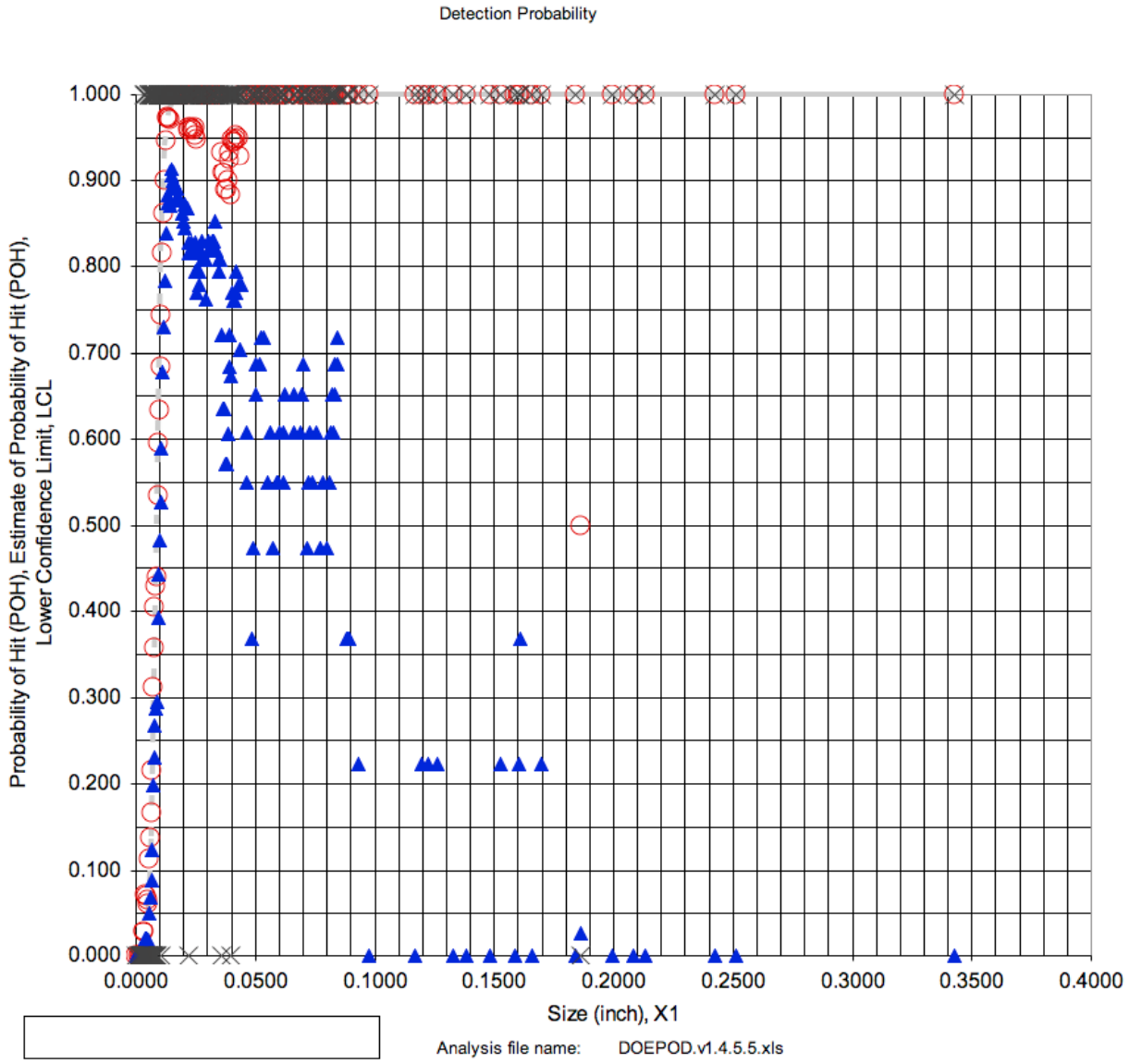
*In summary, satisfy the smallest $X_{POD}$ in Table B that is greater than the largest $X_{POD}$ in Table A, and/or the largest $X_{POD}$ in Table A.*

➢ If this is a survey data set, then only need samples at Survey $X_{POH}$ (if listed), rather than at $X_{POH=1}$

➢ Option: If Optimum $X_{POH}$ < $X_{POH=1}$ then the user may add samples at Optimum $X_{POH}$ rather than at $X_{POH=1.}$ The class width for all added samples at any class length is shown along with the Optimum $X_{POH.}$

➢ Need samples at largest class length, $X_L$

# Case #2




| | |
|---|---|
| File Name = | A8003L.Case2.XLS |
| Data Set Name = | A8003L.Case2(Eci-a-b8 |
| Date & Time = | 5/11/07 4:27 PM |
| Xpod 90/95 Reached Anywhere? | REACHED |
| Classwidth @ 90/95 Xpod = | 0.0040 inch |
| Classlength @ 90/95 Xpod = | 0.0147 inch |
| Actual Lower Confidence Value = | 0.9120 |
| Best LCL = | inch |
| Classwidth @ Best LCL = | inch |
| Classlength @ Best LCL = | inch |
| a(1) [Alpha] = | 39.07 |
| a(2) [Beta] = | 8.21 |
| Chi-Square = | 0.0035 |

*CASE 2 - 90/95 Xpod is reached at a class length. Further VALIDATION is required. Recommend satisfying XL and the smallest Xpod in TABLE B that is greater than the largest Xpod in TABLE A, and/or the largest Xpod in Table A.*

| | |
|---|---|
| Survey/Optimum Xpoh = | 0.000 inch (need Samples) |
| NTIAC 90% POD = | 0.906 @ 0.010 inch |
| NTIAC 90/95 POD = | 0.933 @ 0.015 inch |
| False Call Rate = | with UCL @ 95% = |
| Largest Classlength , XL = | 0.342 inch |
| Samples Needed @ XL = | 28 |
| Classlength Mid-point , Xm = | inch |
| Samples Needed @ Xm = | |
| Smallest Classlength, Xs = | inch |
| Samples Needed @ Xs = | |
| New Smaller Classlength, Xss = | inch |
| BestLCL Classlength, Xlcl = | inch |
| Samples Needed @ Xlcl = | |
| POH Classlength, Xpoh = | inch |
| Samples Needed @ Xpoh = | |
| New Largest Classlength , 2XL = | inch |
| Xm is Near Verification Point = | inch |
| Opt. POD classlength, Xpodopt = | inch |
| Samples Needed @Xpodopt = | |

○ Probability of Hit (POH) in Class Range ▲ Actual Lower Confidence Value (95%, F-distribution) Estimate of POH - Marquardt Gradient/Grid × Hit/Miss

# Case #2

**CASE 2 - 90/95 Xpod is reached at a class length.**

**Further VALIDATION is required.**

**Recommend satisfying XL and the smallest Xpod in TABLE B that is greater than the largest Xpod in TABLE A, and/or the largest Xpod in Table A.**

File Name = A8003L.Case2.XLS
Data Set Name = A8003L.Case2(Eci-a-b8)

## Directed DOE Options

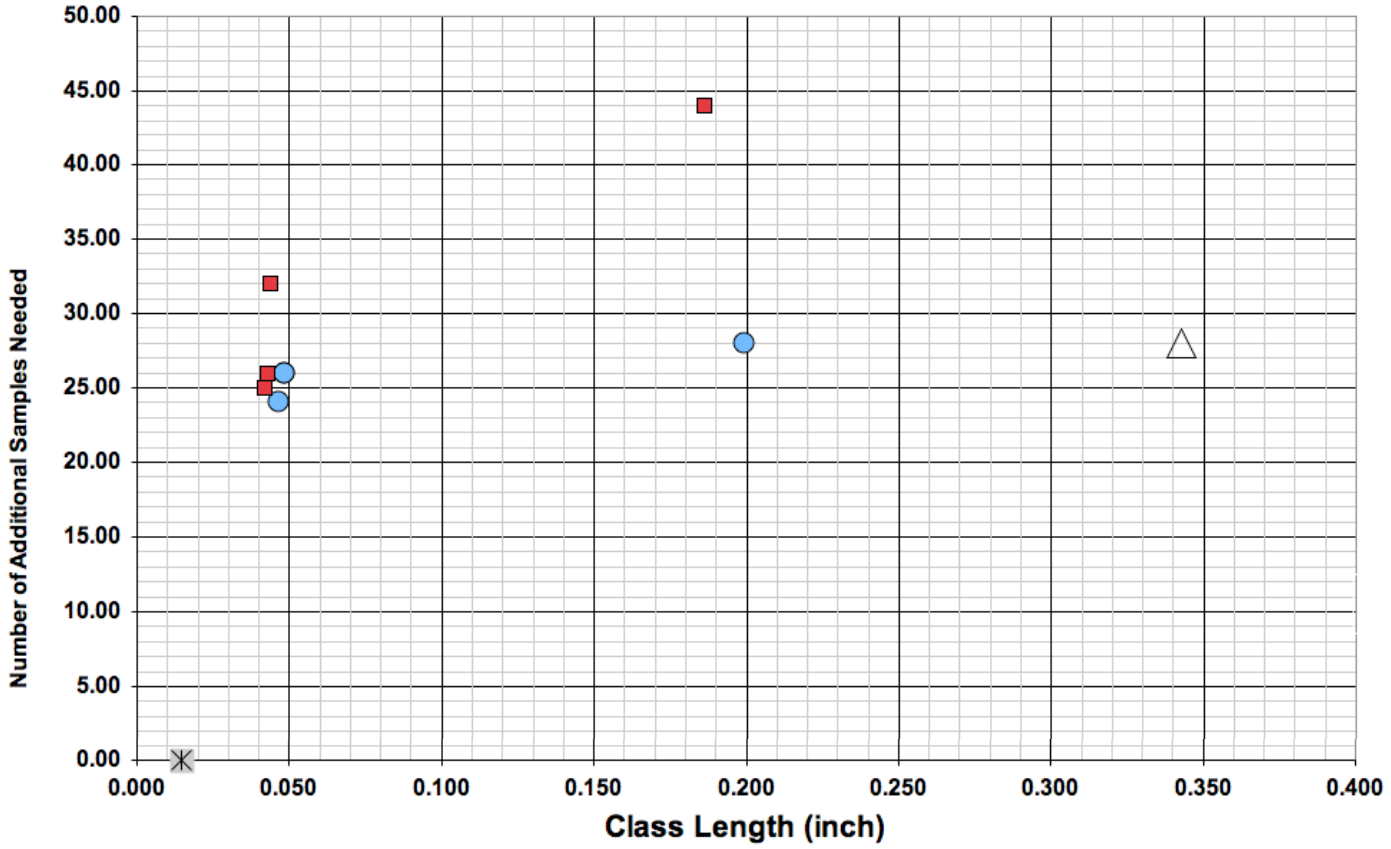



TABLE C

| | Class Length (in) | Additional Samples |
|---|---|---|
| XL = | 0.342 | 28 |
| Xm = | | |
| Xs = | | |
| Xss = | | |
| Xlcl = | | |
| Xpoh = | | |
| 2XL = | | |
| **Alternate Xm = | | |
| Xpodopt = | | |

TABLE A*

*Selected class lengths with existing misses. Each point requires additional samples in or to achieve the Xpod listed.*

| Xpod, Class Length (in) | No. Need |
|---|---|
| 0.1861 | 44 |
| 0.0437 | 32 |
| 0.0429 | 26 |
| 0.0421 | 25 |

TABLE B*

*Selected class lengths with no misses. Additional samples at these class lengths will achieve the Xpod listed.*

| Xpod, Class Length (in) | No. Need |
|---|---|
| 0.1992 | 28 |
| 0.0484 | 26 |
| 0.0464 | 24 |

○ No Misses Observed ■ At Least One Miss Occured △ XL ◇ Xm ○ Xs + Xss ✳ Xlcl ✕ Xpoh ▲ 2XL ✳ Xpod ◆ Xpodopt

# Case #4

- 90/95 $X_{POD}$ Not Reached
- Best LCL is below 0.9 for the best class width group
- No misses at or greater than class length exhibiting the best LCL, $X_{Best\ LCL}$ (i.e., POH =1 everywhere at or greater than class length currently having the best LCL, $X_{Best\ LCL}$)

## *Directed Requirements*

➢ Need samples of $X_{Best\ LCL}$ in class length to achieve 90/95 $X_{POD}$ at $X_{Best\ LCL.}$ $X_{Best\ LCL}$ may equal $X_L$ or $X_{POH=1}$ so that the number of samples listed at this class length are redundantly the same and only one set of samples is needed.

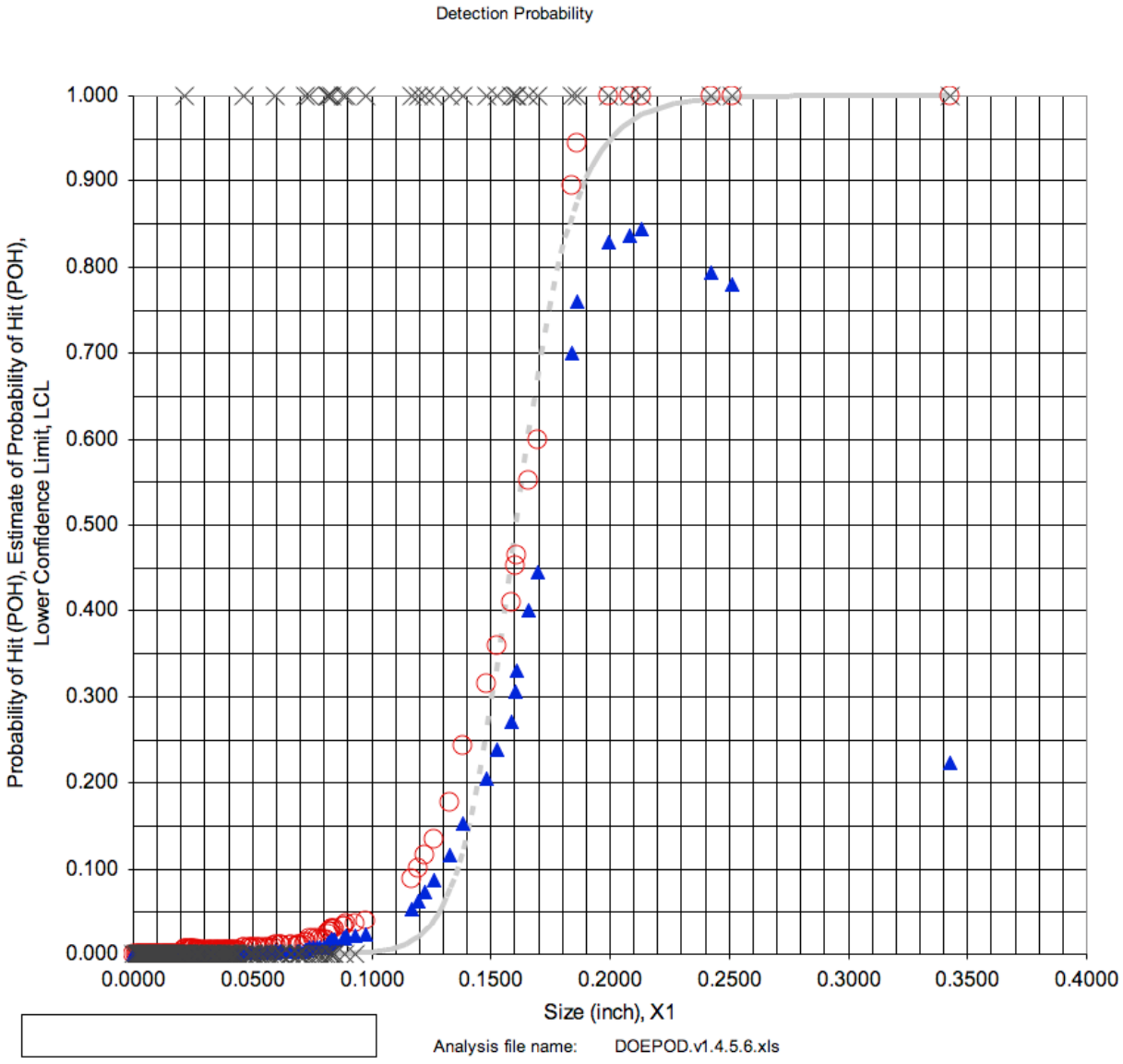
➢

➢ If this is a survey data set, then need to add samples at Survey $X_{POH}$ (if listed), rather than at $X_{POH=1}$

➢

➢ *Option:* If Optimum $X_{POH}$ < $X_{POH=1}$ then the user may add samples at Optimum $X_{POH}$ rather than at $X_{POH=1.}$ The class width for all added samples at any class length is shown along with the Optimum $X_{POH.}$

# Case #4




| | | |
|---|---|---|
| File Name = | C7002L.CASE4.XLS | |
| Data Set Name = | C7002L.CASE4(Lpi-a) | |
| Date & Time = | 6/6/07 10:56 AM | |
| Xpod 90/95 Reached Anywhere? | NOT REACHED | |
| Classwidth @ 90/95 Xpod = | | inch |
| Classlength @ 90/95 Xpod = | | inch |
| Actual Lower Confidence Value = | | |
| Best LCL = | 0.8444 | |
| Classwidth @ Best LCL = | 0.0970 | inch |
| Classlength @ Best LCL = | 0.2131 | inch |
| a(1) [Alpha] = | 24.24 | |
| a(2) [Beta] = | 13.26 | |
| Chi-Square = | 0.0007 | |

*CASE 4 - 90/95 Xpod is not reached anywhere. Recommend satisfying XL and the greater of Xpoh or Xlcl.*

Survey/Optimum Xpoh = 0.0976 -0.004 inch (need 28 Samples)

NTIAC 90% POD = 0.901 @ 0.350 inch

NTIAC 90/95 POD = 0.901 @ 0.580 inch

False Call Rate = with UCL @ 95% =

| | | |
|---|---|---|
| Largest Classlength , XL = | 0.342 | inch |
| Samples Needed @ XL = | 27 | |
| Classlength Mid-point , Xm = | | inch |
| Samples Needed @ Xm = | | |
| Smallest Classlength, Xs = | | inch |
| Samples Needed @ Xs = | | |
| New Smaller Classlength, Xss = | | inch |
| BestLCL Classlength, Xlcl = | 0.213 | inch |
| Samples Needed @ Xlcl = | 11 | |
| POH Classlength, Xpoh = | 0.199 | inch |
| Samples Needed @ Xpoh = | 13 | |
| New Largest Classlength , 2XL = | | inch |
| Xm is Near Verification Point = | | inch |
| Opt. POD classlength, Xpodopt = | | inch |
| Samples Needed @Xpodopt = | | |

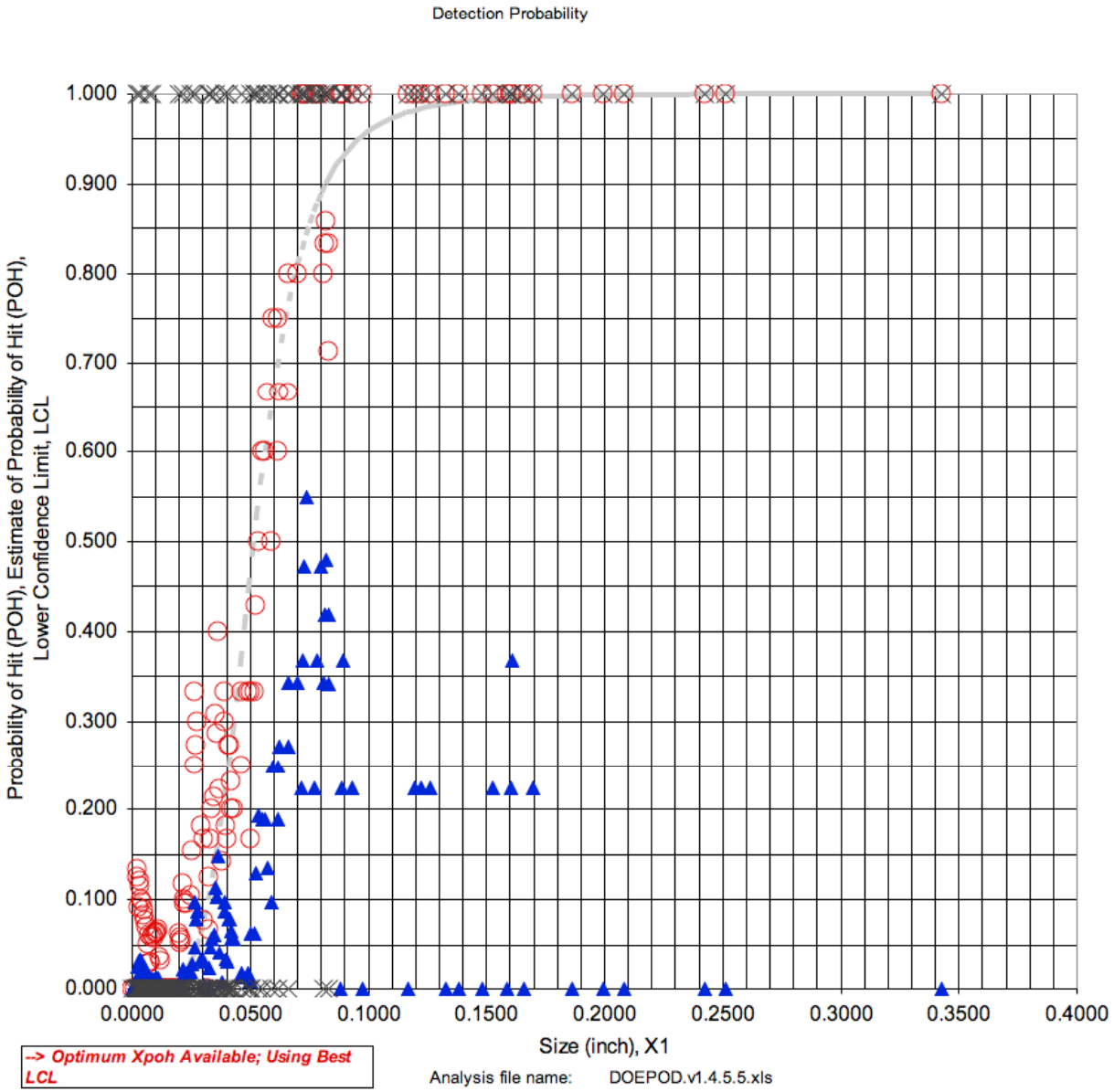
# Case #5

- 90/95 $X_{POD}$ Not Reached
- Best LCL is below 0.9 for the best class width group
- There are misses at or greater than class length $X_{Best\ LCL}$
- There exists a class length, $X_{POH=1}$, above which there are no misses.
- There are no misses for class lengths equal to greater than $X_L/3$ (i.e., $X_{POH=1} \leq X_L/3$)
- $X_{POH=1} \leq X_L/3$ so that POH is not fluctuating at larger class lengths. Use $X_{POH=1}$ as the trial $X_{POD}$

***Directed Requirements***

- Need samples of $X_{POH=1}$
- If this is a survey data set, then need to add samples at Survey $X_{POH}$ (if listed), rather than at $X_{POH=1}$
- Option: If Optimum $X_{POH} < X_{POH=1}$ then the user may add samples at Optimum $X_{POH}$ rather than at $X_{POH=1}$. The class width for all added samples at any class length is shown along with the Optimum $X_{POH}$.
- Need 29 samples largest class length, $X_L$

# Case #5




| | |
|---|---|
| File Name = | C7001L.Case5.XLS |
| Data Set Name = | C7001L.Case5(Lpi-a) |
| Date & Time = | 5/11/07 4:31 PM |
| Xpod 90/95 Reached Anywhere? | NOT REACHED |
| Classwidth @ 90/95 Xpod = | inch |
| Classlength @ 90/95 Xpod = | inch |
| Actual Lower Confidence Value = | |
| Best LCL = | 0.5493 |
| Classwidth @ Best LCL = | 0.0040 inch |
| Classlength @ Best LCL = | 0.0738 inch |
| a(1) [Alpha] = | 14.03 |
| a(2) [Beta] = | 4.74 |
| Chi-Square = | 0.0086 |

*CASE 5 - 90/95 Xpod is not reached anywhere.*
*Recommend satisfying XL and Xpoh.*

Survey/Optimum Xpoh = 0.0881 -0.004 inch (need 28 Samples)

| | | | |
|---|---|---|---|
| NTIAC 90% POD = | 0.903 | @ 0.215 | inch |
| NTIAC 90/95 POD = | 0.901 | @ 0.360 | inch |

False Call Rate = with UCL @ 95% =

| | | |
|---|---|---|
| Largest Classlength , XL = | 0.342 | inch |
| Samples Needed @ XL = | 28 | |
| Classlength Mid-point , Xm = | | inch |
| Samples Needed @ Xm = | | |
| Smallest Classlength, Xs = | | inch |
| Samples Needed @ Xs = | | |
| New Smaller Classlength, Xss = | | inch |
| BestLCL Classlength, Xlcl = | | inch |
| Samples Needed @ Xlcl = | | |
| POH Classlength, Xpoh = | 0.088 | inch |
| Samples Needed @ Xpoh = | 28 | |
| New Largest Classlength , 2XL = | | inch |
| Xm is Near Verification Point = | | inch |
| Opt. POD classlength, Xpodopt = | | inch |
| Samples Needed @Xpodopt = | | |

○ Probability of Hit (POH) in Class Range ▲ Actual Lower Confidence Value (95%, F-distribution) Estimate of POH - Marquardt Gradient/Grid × Hit/Miss

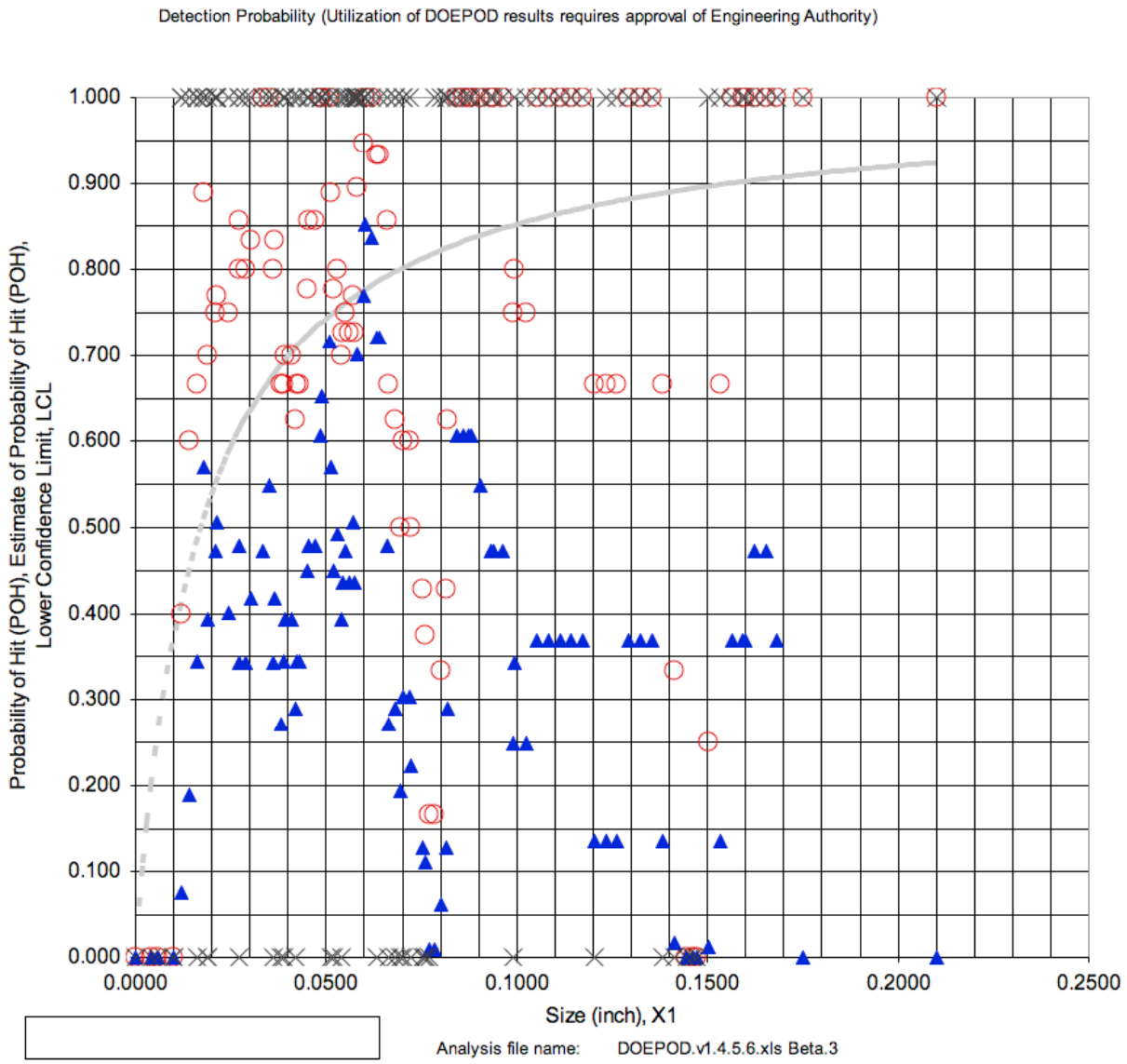
# Case #6

- 90/95 $X_{POD}$ Not Reached
- Best LCL is below 0.9 for the best class width group
- There are misses at or greater than class length $X_{Best\ LCL}$
- There exists a class length, $X_{POH=1}$, above which there are no misses.
- There are are misses for class lengths greater than $X_L$ /3 (i.e., $X_{POH=1} \geq X_L$ /3)
- $X_{POH=1} \geq X_L$ /3 so that POH may be fluctuating rapidly.

## *Directed Requirements*

- Need to expand current range of $X_L$ by adding new samples with class lengths of $2X_L$ or greater
- Need samples of $X_{POH=1}$. $X_{POH=1}$ may equal $X_L$ so that the number of samples at this class length are redundantly the same and only one set of samples is needed.
- Need 29 samples at largest class length, $2X_L$
- If this is a survey data set, then need to add samples at Survey $X_{POH}$ (if listed), rather than at $X_{POH=1}$
- Option: If Optimum $X_{POH} < X_{POH=1}$ then the user may add samples at Optimum $X_{POH}$ rather than at $X_{POH=1}$. The class width for all added samples at any class length is shown along with the Optimum $X_{POH}$.

# Case #6




| | | |
|---|---|---|
| File Name = | B1003AD.Case6.XLS | |
| Data Set Name = | B1003AD.Case6(CRK | |
| Date & Time = | 8/6/07 3:22 PM | |
| Xpod 90/95 Reached Anywhere? | NOT REACHED | |
| Classwidth @ 90/95 Xpod = | | inch |
| Classlength @ 90/95 Xpod = | | inch |
| Actual Lower Confidence Value = | | |
| Best LCL = | 0.8514 | |
| Classwidth @ Best LCL = | 0.0060 | inch |
| Classlength @ Best LCL = | 0.0603 | inch |
| a(1) [Alpha] = | 4.03 | |
| a(2) [Beta] = | 0.99 | |
| Chi-Square = | 0.0743 | |

*CASE 6 - 90/95 Xpod is not reached anywhere.*
*Recommend satisfying XL, Xpoh, and 2XL.*

Survey/Optimum Xpoh = 0.1503 -0.002 inch (need 28 Samples)

| | | |
|---|---|---|
| NTIAC 90% POD = | @ | inch |
| NTIAC 90/95 POD = | @ | inch |
| False Call Rate = | with UCL @ 95% = | |
| Largest Classlength , XL = | 0.210 | inch |
| Samples Needed @ XL = | 28 | |
| Classlength Mid-point , Xm = | | inch |
| Samples Needed @ Xm = | | |
| Smallest Classlength, Xs = | | inch |
| Samples Needed @ Xs = | | |
| New Smaller Classlength, Xss = | | inch |
| BestLCL Classlength, Xlcl = | | inch |
| Samples Needed @ Xlcl = | | |
| POH Classlength, Xpoh = | 0.156 | inch |
| Samples Needed @ Xpoh = | 26 | |
| New Largest Classlength , 2XL = | 0.420 | inch |
| Xm is Near Verification Point = | | inch |
| Opt. POD classlength, Xpodopt = | | inch |
| Samples Needed @Xpodopt = | | |

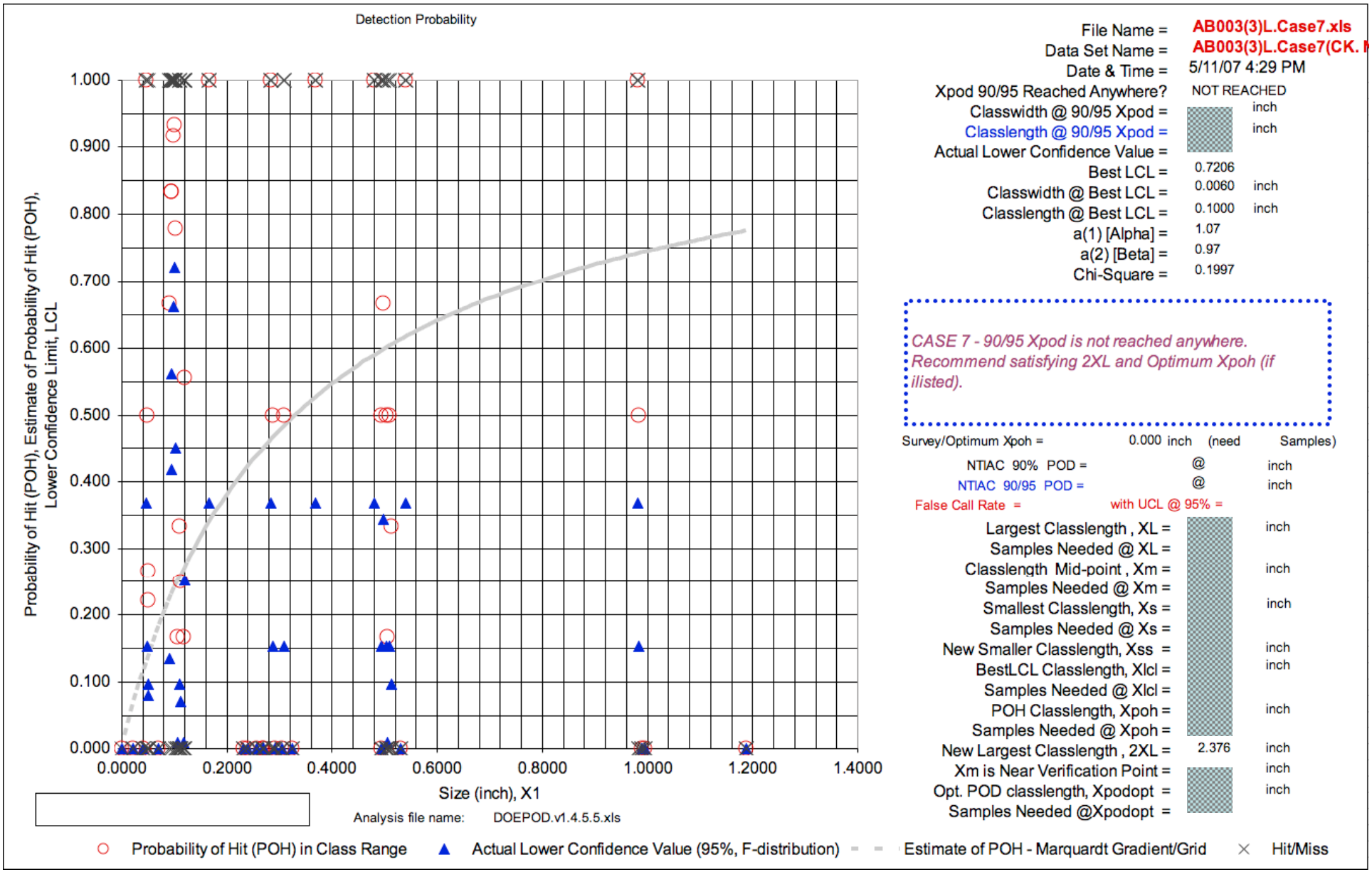
# Case #7

- 90/95 $X_{POD}$ Not Reached
- Best LCL is below 0.9 for the best class width group
- There are misses at or greater than class length $X_{Best\ LCL}$
- There does **NOT** exist a class length, $X_{POH=1}$, above which there are no misses.
- POH may be fluctuating rapidly
- There may be no hits anywhere

## *Directed Requirements*

- Inspection system may not be appropriate for meeting inspection criteria
- If this is a survey data set, then need to add samples at Survey $X_{POH}$ (if listed)
- Option: The user may add samples at Optimum $X_{POH.}$ The class width for all added samples at any class length is shown along with the Optimum $X_{POH.}$
- Need to expand current range of $X_L$ by adding new samples with class lengths of $2X_L$ or greater
- Need 29 samples at largest class length, $2X_L$

# Case #7


Detection Probability
Probability of Hit (POH), Estimate of Probability of Hit (POH), Lower Confidence Limit, LCL
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0000
0.2000
0.4000
0.6000
0.8000
1.0000
1.2000
1.4000
Size (inch), X1
Analysis file name: DOEPOD.v1.4.5.5.xls
File Name = AB003(3)L.Case7.xls
Data Set Name = AB003(3)L.Case7(CK. M
Date & Time = 5/11/07 4:29 PM
Xpod 90/95 Reached Anywhere? NOT REACHED
Classwidth @ 90/95 Xpod = inch
Classlength @ 90/95 Xpod = inch
Actual Lower Confidence Value =
Best LCL = 0.7206
Classwidth @ Best LCL = 0.0060 inch
Classlength @ Best LCL = 0.1000 inch
a(1) [Alpha] = 1.07
a(2) [Beta] = 0.97
Chi-Square = 0.1997
CASE 7 - 90/95 Xpod is not reached anywhere. Recommend satisfying 2XL and Optimum Xpoh (if ilisted).
Survey/Optimum Xpoh = 0.000 inch (need Samples)
NTIAC 90% POD = @ inch
NTIAC 90/95 POD = @ inch
False Call Rate = with UCL @ 95% =
Largest Classlength , XL = inch
Samples Needed @ XL =
Classlength Mid-point , Xm = inch
Samples Needed @ Xm =
Smallest Classlength, Xs = inch
Samples Needed @ Xs =
New Smaller Classlength, Xss = inch
BestLCL Classlength, Xlcl = inch
Samples Needed @ Xlcl =
POH Classlength, Xpoh = inch
Samples Needed @ Xpoh =
New Largest Classlength , 2XL = 2.376 inch
Xm is Near Verification Point = inch
Opt. POD classlength, Xpodopt = inch
Samples Needed @Xpodopt =
Probability of Hit (POH) in Class Range
Actual Lower Confidence Value (95%, F-distribution)
Estimate of POH - Marquardt Gradient/Grid
Hit/Miss

# Survey and Optimized $X_{POH}$ Data Sets

• This data set has insufficient number of samples for unconstrained class width optimization

• The class width optimization has determined that there is a class width for which the smallest $X_{POH=1}$ class length is identified. The Survey and Optimum $X_{POH}$ class lengths and class widths are identified on the charts as Survey/Optimum $X_{POH}$.

- For example, the listing:

**Survey/Optimum $X_{POH}$ = 0.0500 – 0.015 inch (need 18 samples)**

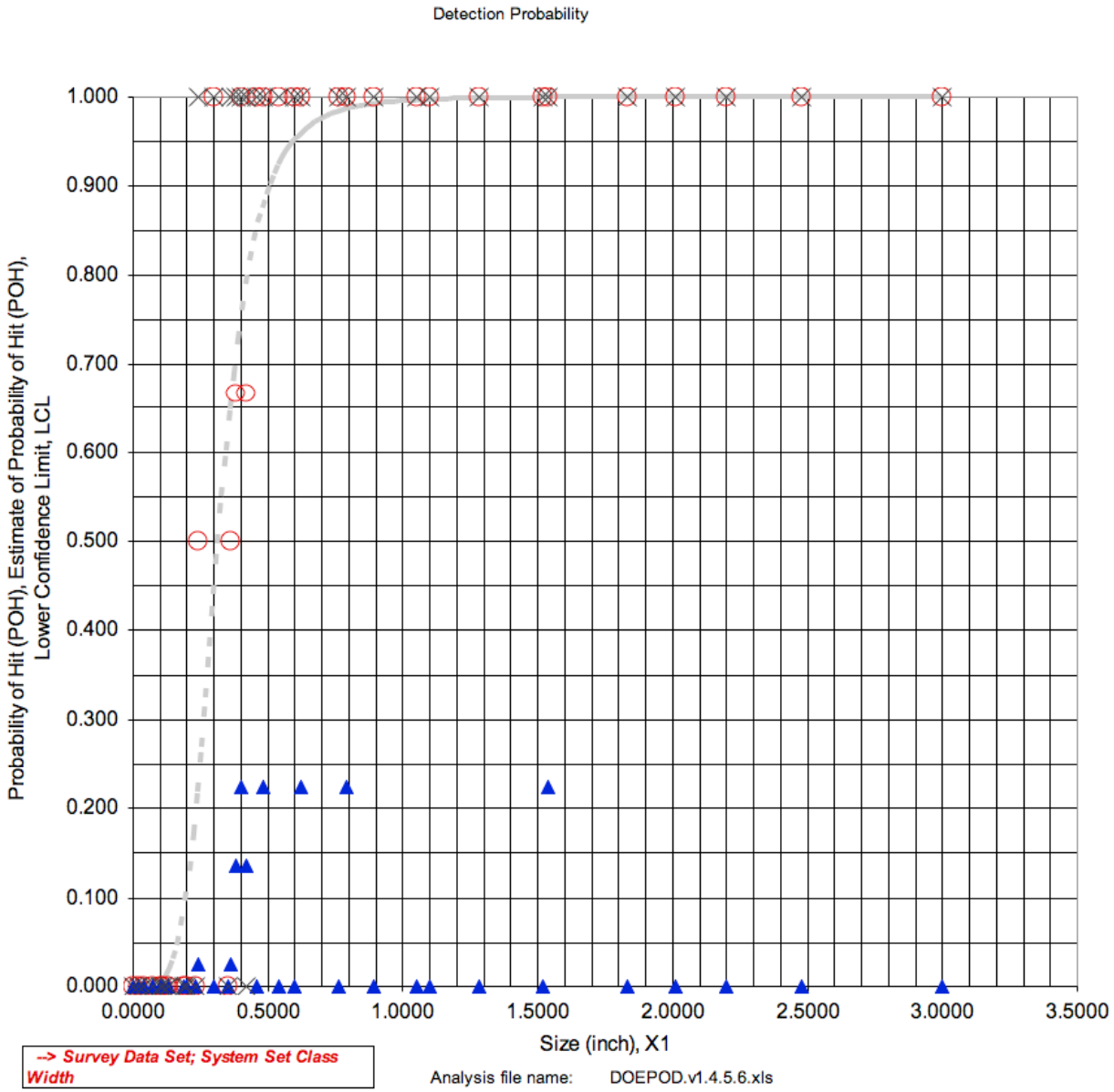
indicates that a class width of 0.015” has been used and the Survey or Optimum $X_{POH}$ occurs at 0.0500”, and that 18 additional samples may be added to achieve $X_{POD}$ add at that class length. The added samples should have sizes that range anywhere between 0.0500” and 0.035”, inclusively.

• If Survey/Optimum $X_{POH}$ is pursued, then the class width for all added samples at any other class length is to be the same as that for Survey/Optimum $X_{POH}$.

## *Directed Requirements*

- Need samples at Survey/Optimum $X_{POH}$
- Need samples at $X_L$
- Survey results are not available when user sets the class width

# Case #5 - Survey




| | |
|---|---|
| File Name = | Survey.Case5.xls |
| Data Set Name = | Survey.Case5(Survey C |
| Date & Time = | 5/14/07 9:23 AM |
| Xpod 90/95 Reached Anywhere? | NOT REACHED |
| Classwidth @ 90/95 Xpod = | inch |
| Classlength @ 90/95 Xpod = | inch |
| Actual Lower Confidence Value = | |
| Best LCL = | 0.2236 |
| Classwidth @ Best LCL = | 0.0390 inch |
| Classlength @ Best LCL = | 0.4000 inch |
| a(1) [Alpha] = | 5.36 |
| a(2) [Beta] = | 4.65 |
| Chi-Square = | 0.0296 |

*CASE 5 - This is a survey data set. 90/95 Xpod is not reached anywhere. Recommend satisfying XL and Survey Xpoh (if listed)*

Survey/Optimum Xpoh = 0.4600 -0.039 inch (need 28 Samples)

NTIAC 90% POD = @ inch

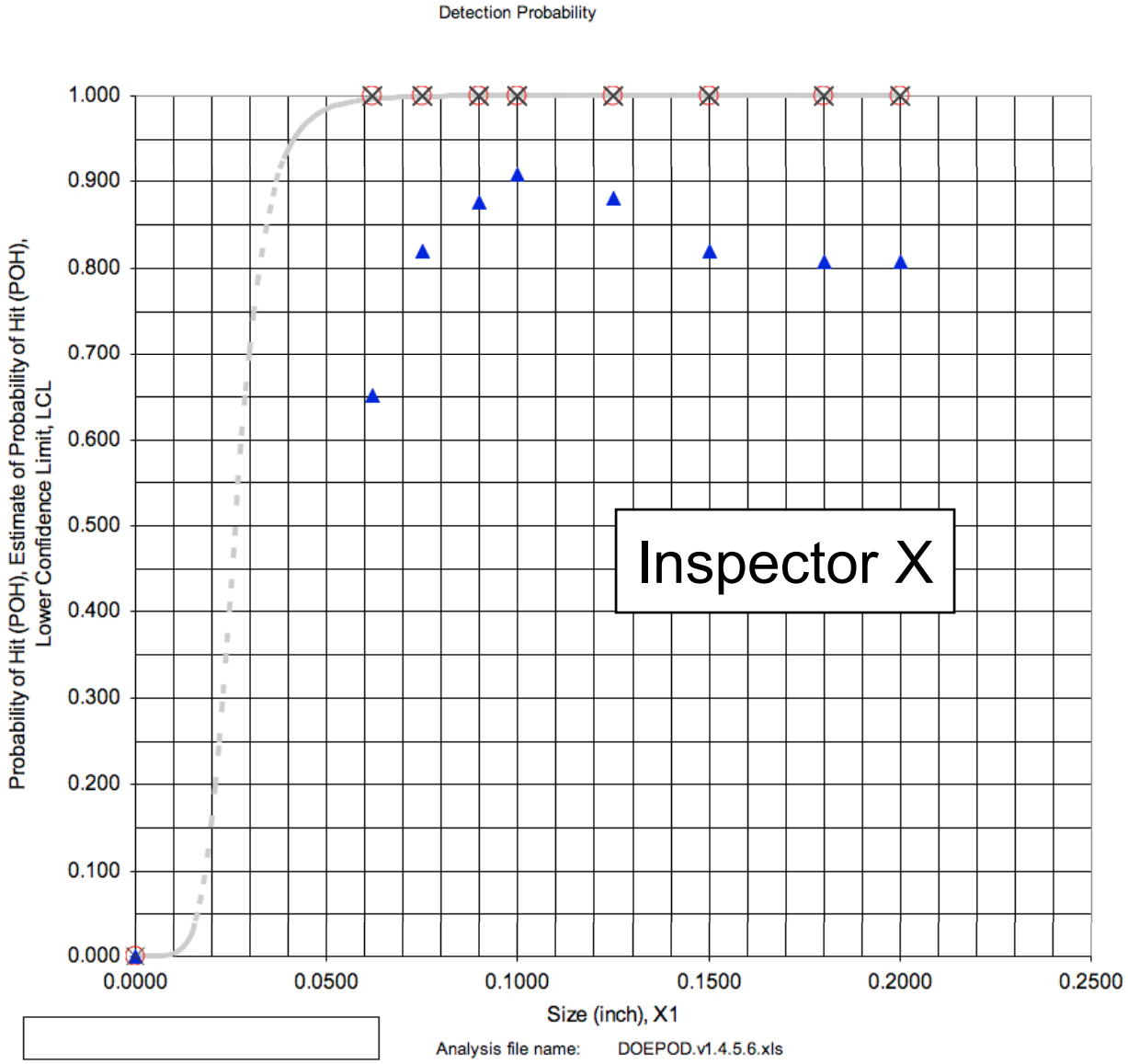
NTIAC 90/95 POD = @ inch

False Call Rate = with UCL @ 95% =

| | |
|---|---|
| Largest Classlength , XL = | 3.000 inch |
| Samples Needed @ XL = | 28 |
| Classlength Mid-point , Xm = | inch |
| Samples Needed @ Xm = | |
| Smallest Classlength, Xs = | inch |
| Samples Needed @ Xs = | |
| New Smaller Classlength, Xss = | inch |
| BestLCL Classlength, Xlcl = | inch |
| Samples Needed @ Xlcl = | |
| POH Classlength, Xpoh = | 0.460 inch |
| Samples Needed @ Xpoh = | 28 |
| New Largest Classlength , 2XL = | inch |
| Xm is Near Verification Point = | inch |
| Opt. POD classlength, Xpodopt = | inch |
| Samples Needed @Xpodopt = | |

# DOEPOD Example

## Does the fastener type affect the capability of the inspection system?




| | | |
|---|---|---|
| File Name = | | |
| Data Set Name = | | |
| Date & Time = | 6/5/07 8:10 AM | |
| Xpod 90/95 Reached Anywhere? | REACHED | |
| Classwidth @ 90/95 Xpod = | 0.0380 | inch |
| Classlength @ 90/95 Xpod = | 0.1000 | inch |
| Actual Lower Confidence Value = | 0.9070 | |
| Best LCL = | | |
| Classwidth @ Best LCL = | | inch |
| Classlength @ Best LCL = | | inch |
| a(1) [Alpha] = | 23.11 | |
| a(2) [Beta] = | 6.34 | |
| Chi-Square = | 0.0000 | |

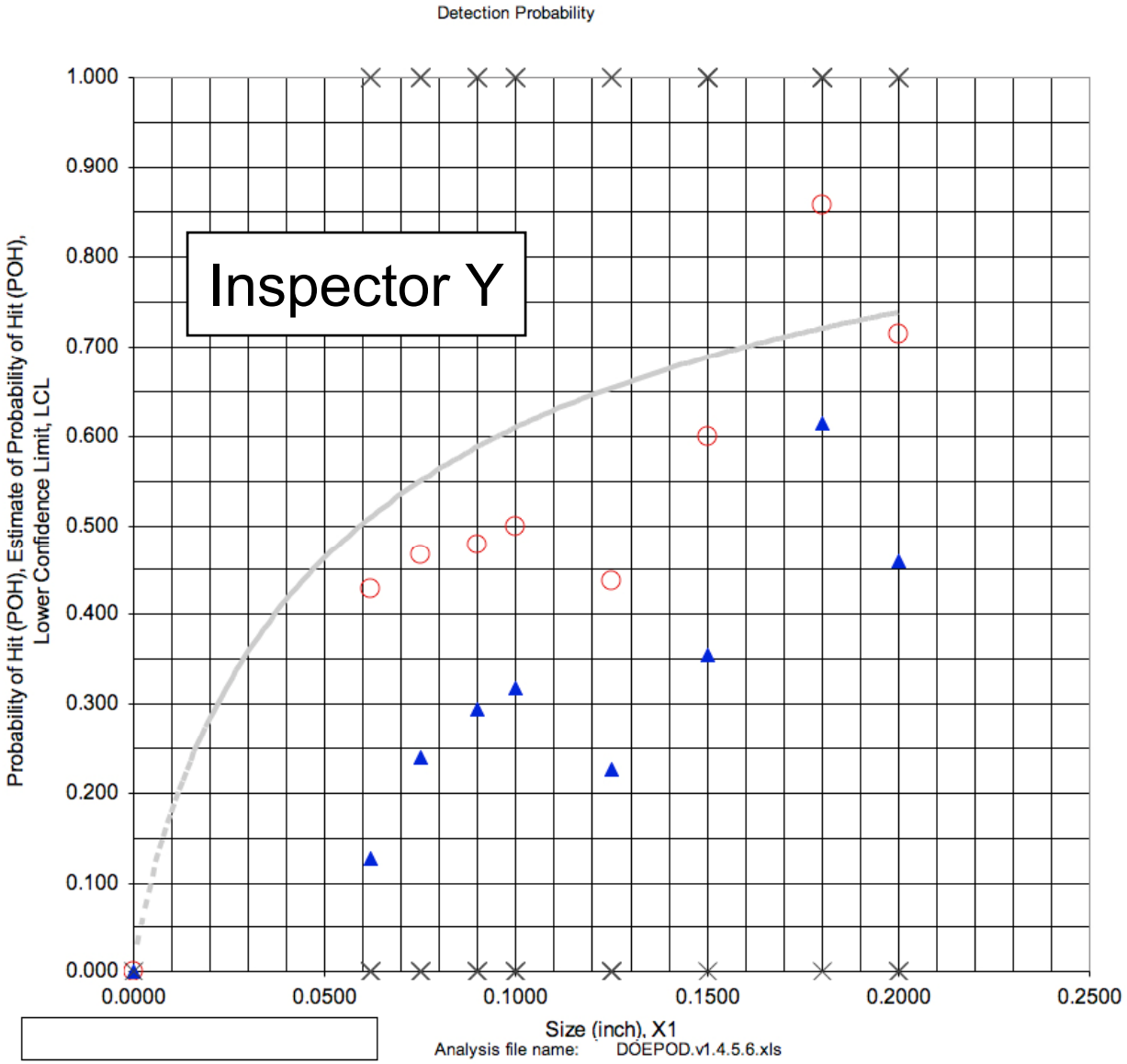
*CASE 1 - 90/95 Xpod is VALIDATED from Xpod to XL when XL and Xm are satisfied. An alternate 90/95 Xpod is available if Xpodpot or Optimum Xpoh (if listed) is also satisfied.*

Survey/Optimum Xpoh = 0.0620 -0.038 inch (need 22 Samples)

| | | |
|---|---|---|
| NTIAC 90% POD = | @ | inch |
| NTIAC 90/95 POD = | @ | inch |
| False Call Rate = | with UCL @ 95% = | |
| Largest Classlength , XL = | 0.200 | inch |
| Samples Needed @ XL = | 15 | |
| Classlength Mid-point , Xm = | 0.125 | inch |
| Samples Needed @ Xm = | 5 | |
| Smallest Classlength, Xs = | | inch |
| Samples Needed @ Xs = | | |
| New Smaller Classlength, Xss = | | inch |
| BestLCL Classlength, Xlcl = | | inch |
| Samples Needed @ Xlcl = | | |
| POH Classlength, Xpoh = | | inch |
| Samples Needed @ Xpoh = | | |
| New Largest Classlength , 2XL = | | inch |
| Xm is Near Verification Point = | | inch |
| Opt. POD classlength, Xpodopt = | 0.0620 | inch |
| Samples Needed @Xpodopt = | 22 | |

○ Probability of Hit (POH) in Class Range ▲ Actual Lower Confidence Value (95%, F-distribution) Estimate of POH - Marquardt Gradient/Grid × Hit/Miss

# DOEPOD Example (continued)




| | |
|---|---|
| File Name = | |
| Data Set Name = | |
| Date & Time = | 6/5/07 8:22 AM |
| Xpod 90/95 Reached Anywhere? | NOT REACHED |
| Classwidth @ 90/95 Xpod = | inch |
| Classlength @ 90/95 Xpod = | inch |
| Actual Lower Confidence Value = | |
| Best LCL = | 0.6146 |
| Classwidth @ Best LCL = | 0.0300 inch |
| Classlength @ Best LCL = | 0.1800 inch |
| a(1) [Alpha] = | 2.41 |
| a(2) [Beta] = | 0.85 |
| Chi-Square = | 0.0157 |

*CASE 7 - 90/95 Xpod is not reached anywhere. Recommend satisfying 2XL and Optimum Xpoh (if ilisted).*

Survey/Optimum Xpoh = 0.000 inch (need Samples)

| | |
|---|---|
| NTIAC 90% POD = | @ inch |
| NTIAC 90/95 POD = | @ inch |
| False Call Rate = | with UCL @ 95% = |
| Largest Classlength , XL = | inch |
| Samples Needed @ XL = | |
| Classlength Mid-point , Xm = | inch |
| Samples Needed @ Xm = | |
| Smallest Classlength, Xs = | inch |
| Samples Needed @ Xs = | |
| New Smaller Classlength, Xss = | inch |
| BestLCL Classlength, Xlcl = | inch |
| Samples Needed @ Xlcl = | |
| POH Classlength, Xpoh = | inch |
| Samples Needed @ Xpoh = | |
| New Largest Classlength , 2XL = | 0.400 inch |
| Xm is Near Verification Point = | inch |
| Opt. POD classlength, Xpodopt = | inch |
| Samples Needed @Xpodopt = | |

○ Probability of Hit (POH) in Class Range ▲ Actual Lower Confidence Value (95%, F-distribution) Estimate of POH - Marquardt Gradient/Grid × Hit/Miss

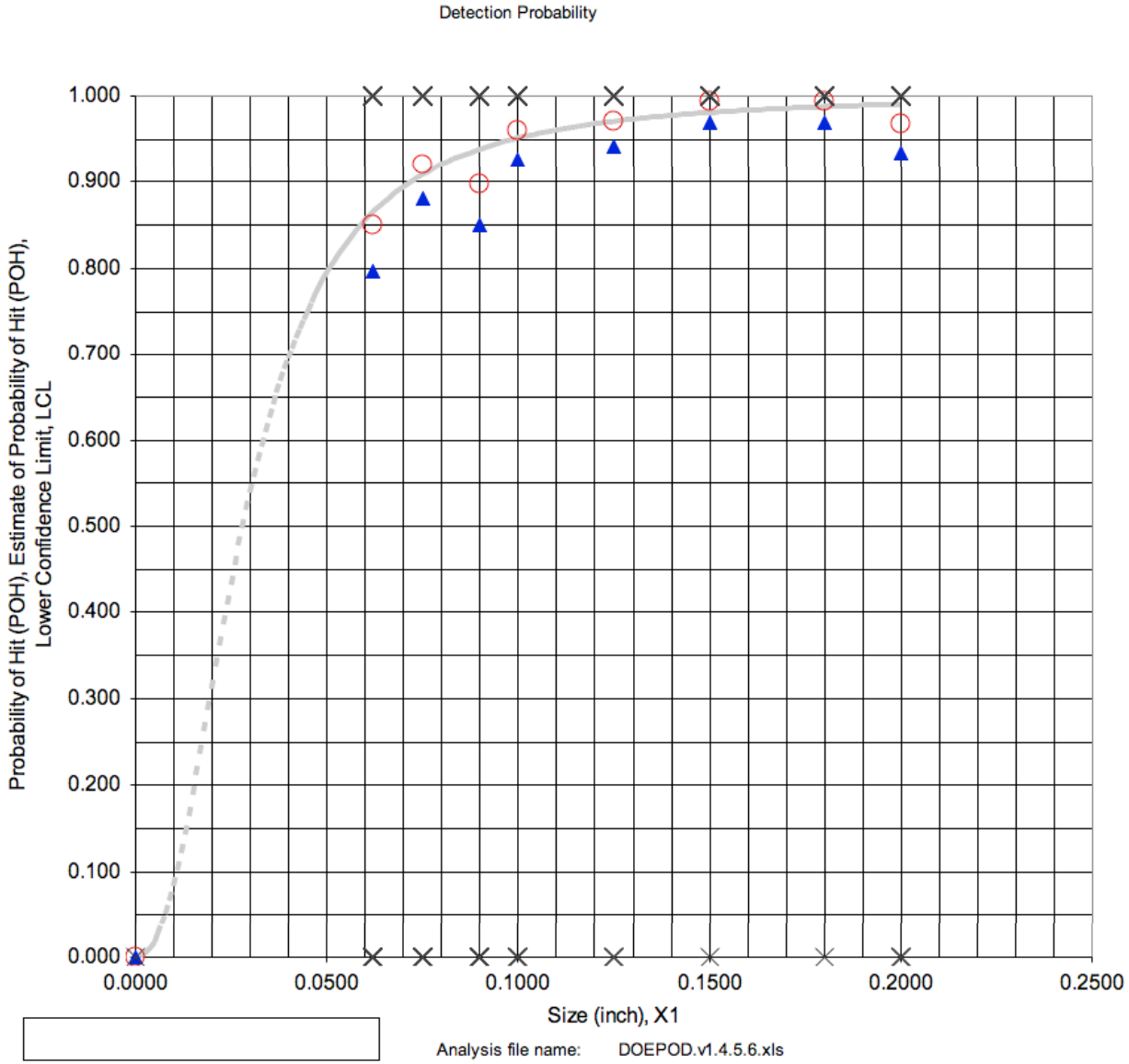
# DOEPOD Example (continued)

## Does the fastener type affect the capability of the inspection system?

| Multi-Fasteners | Inspector | 90/95 Xpod (in) | Optimum Xpoh (Best Xpod that could be achieved if test specimens are added) (in) | DOEPOD v1.4.5.6 | 5-Jun-07 |
|---|---|---|---|---|---|
| | 1 | 0.100 | 0.062 | CASE 1 | 90/95 Xpod reached |
| | 2 | 0.100 | 0.062 | CASE 1 | 90/95 Xpod reached |
| | 3 | 0.100 | 0.062 | CASE 1 | 90/95 Xpod reached |
| | 4 | 0.100 | 0.062 | CASE 1 | 90/95 Xpod reached |
| | 5 | 0.100 | 0.062 | CASE 1 | 90/95 Xpod reached |
| | 6 | 0.100 | 0.062 | CASE 1 | 90/95 Xpod reached |
| | 7 | 0.100 | 0.062 | CASE 1 | 90/95 Xpod reached |
| | 8 | 0.100 | 0.062 | CASE 1 | 90/95 Xpod reached |
| | 9 | 0.100 | 0.062 | CASE 1 | 90/95 Xpod reached |
| | 10 | 0.150 | 0.090 | CASE 1 | 90/95 Xpod reached |
| | 11 | 0.200 | 0.100 | CASE 1 | 90/95 Xpod reached |
| | 12 | 0.200 | 0.100 | CASE 1 | 90/95 Xpod reached |
| | 13 | 0.200 | 0.100 | CASE 1 | 90/95 Xpod reached |
| | 14 | 0.200 | 0.100 | CASE 1 | 90/95 Xpod reached |
| | 15 | 0.200 | 0.100 | CASE 1 | 90/95 Xpod reached |
| | 16 | 0.200 | 0.100 | CASE 1 | 90/95 Xpod reached |
| | 17 | 0.200 | 0.100 | CASE 1 | 90/95 Xpod reached |
| | 18 | 0.200 | 0.125 | CASE 1 | 90/95 Xpod reached |
| | 19 | 0.200 | 0.125 | CASE 1 | 90/95 Xpod reached |
| | | | | | 90/95 Xpod reached but |
| | 20 | 0.100 | see table A | CASE 2 | miss at largest flaw size |
| | 21 | not reached | | CASE 7 | Miss at largest flaw size |
| | 22 | not reached | | CASE 7 | Miss at largest flaw size |

# DOEPOD Example (continued)

## All Inspectors




| | |
|---|---|
| File Name = | |
| Data Set Name = | |
| Date & Time = | 5/31/07 5:15 PM |
| Xpod 90/95 Reached Anywhere? | REACHED |
| Classwidth @ 90/95 Xpod = | 0.0010 inch |
| Classlength @ 90/95 Xpod = | 0.1000 inch |
| Actual Lower Confidence Value = | 0.9260 |
| Best LCL = | inch |
| Classwidth @ Best LCL = | inch |
| Classlength @ Best LCL = | inch |
| a(1) [Alpha] = | 8.33 |
| a(2) [Beta] = | 2.33 |
| Chi-Square = | 0.0004 |

*CASE 1 - 90/95 Xpod is NOW VALIDATED from Xpod to XL. An alternate 90/95 Xpod is available if Xpodpot or Optimum Xpoh (if listed) is also satisfied.*

| | | | |
|---|---|---|---|
| Survey/Optimum Xpoh = | 0.000 inch | (need | Samples) |
| NTIAC 90% POD = | @ | | inch |
| NTIAC 90/95 POD = | @ | | inch |
| False Call Rate = | with UCL @ 95% = | | |
| Largest Classlength , XL = | 0.200 | | inch |
| Samples Needed @ XL = | 0 | | |
| Classlength Mid-point , Xm = | 0.150 | | inch |
| Samples Needed @ Xm = | | | |
| Smallest Classlength, Xs = | | | inch |
| Samples Needed @ Xs = | | | |
| New Smaller Classlength, Xss = | | | inch |
| BestLCL Classlength, Xlcl = | | | inch |
| Samples Needed @ Xlcl = | | | |
| POH Classlength, Xpoh = | | | inch |
| Samples Needed @ Xpoh = | | | |
| New Largest Classlength , 2XL = | | | inch |
| Xm is Near Verification Point = | | | inch |
| Opt. POD classlength, Xpodopt = | 0.0950 | | inch |
| Samples Needed @Xpodopt = | 29 | | |

○ Probability of Hit (POH) in Class Range ▲ Actual Lower Confidence Value (95%, F-distribution) Estimate of POH - Marquardt Gradient/Grid × Hit/Miss

# False Calls

- False Calls are handled similarly except the upper confidence limit* $P_u$ is used

$$False\ Call\ Rate = \frac{Number\ of\ False\ Calls\ (X)}{Number\ of\ False\ Call\ Opportunities\ (N)}$$

$$P_u = \frac{(X+1)\,F_\alpha(f_1, f_2)}{(N-X)+(X+1)\,F_\alpha(f_1, f_2)}\ , \quad \left\{ \begin{array}{l} f_1 = 2(X+1) \\ f_2 = 2(N-X) \end{array} \right\}$$

- 95% Chance that the false call rate is less than or equal to the $P_u$

# False Calls

• Test samples with no flaws present may be included in DOEPOD for determination of false call rate and the upper confidence value of the false call rate at 95% confidence. For test samples with no flaw present, enter flaw size of 0.00001”

• False call rate may be explored and optimized by adjusting signal amplitude threshold.

• *Warning: May reach 90/95 $X_{POD}$ at cost of increasing false call rate.* Need to know what false call rate is acceptable.

• False calls rate should not be accepted as is without first addressing the cause of the false call and identifying procedures to remove false calls. May need to modify or add inspection protocols.

# DOEPOD Data Entry

## Hit / Miss Data

| ID Number | CRACK SIZE (inches) | DEPTH | HIT/MISS (0 or 100) | Signal Amplitude Measured (Arbitrary Units) | SIGNAL TREASHOLD |
|---|---|---|---|---|---|
| | 0.342 | | 100 | | |
| | 0.251 | | 100 | | |
| | 0.242 | | 100 | | |
| | 0.213 | | 100 | | |
| | 0.208 | | 100 | | |
| | 0.199 | | 100 | | |
| | 0.186 | | 100 | | |
| | 0.184 | | 0 | | |
| | 0.169 | | 100 | | |
| | 0.166 | | 0 | | |

## Signal Amplitude Data

| ID Number | CRACK SIZE (inches) | DEPTH | HIT/MISS (0 or 100) | Signal Amplitude Measured (Arbitrary Units) | SIGNAL TREASHOLD |
|---|---|---|---|---|---|
| | 0.342 | | | 0.5 | 0.025 |
| | 0.251 | | | 0.4 | |
| | 0.242 | | | 0.3 | |
| | 0.213 | | | 0.2 | |
| | 0.208 | | | 0.1 | |
| | 0.199 | | | 0.05 | |
| | 0.186 | | | 0.025 | |
| | 0.184 | | | 0.01 | |
| | 0.169 | | | 0.025 | |
| | 0.166 | | | 0.01 | |

# DOEPOD REQUIREMENTS

• Inspection processes are to be under control and fixed.

• Multiple inspection processes may be used on the same set of test samples with the constraint that Directed DOE POD is to be executed for each process separately. When multiple inspection processes or systems are used, the resulting directed sample requirements may be overlapping. In this situation, the user is to keep the non-overlapping directed sample requirements applied to the appropriate inspection process, while utilizing overlapping directed sample requirements for the multiple processes in order to minimize the number of generated test samples.

• There are to be an equal number of unflawed samples during any test.

• There are to be more than two (2) samples at different class lengths.

• A moving class width that groups flaws of similar size is used to optimize the lower confidence value. This moving class width and the best lower confidence bound (value) optimization will be invoked if there are more than four (4) samples at different class lengths.

• Flaw sizes must be greater than 0.00001”

• Test samples with no flaws present may be included for determination of false call rate and the upper confidence value of the false call rate at 95% confidence. For test samples with no flaw present, enter flaw size of 0.00001”

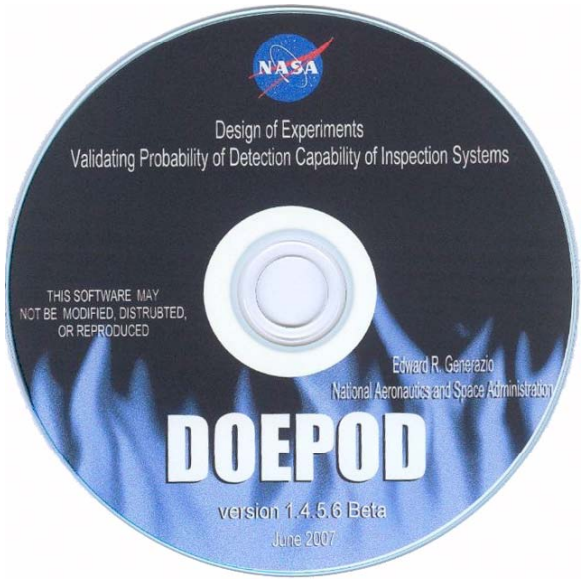
• The maximum number of test samples is 1999.

• Be prepared to generate, inspect, and evaluate test samples during the NDE technology capability determination.

• Validated 90/95 $X_{POD}$ is obtained when the user has reached and satisfied the sample requirements of Case 1. **That is, there is a 95% chance that the probability of detection of the system is greater than 90% for class lengths in the range 90/95 $X_{POD}$ to XL.**

# SUMMARY

- Concept for Binomialization of Test Data
- Process for determining observed probability of hit (POH) and associated confidence limits
- Utilization of moving class width to group flaws and for flaw class width optimization
- Identification of POD CASES and directed actions needed to validate inspection systems.
- False call rate and confidence
- DOEPOD Data Entry
- DOEPOD Beta (2,500 lines of code, PC and MAC, limited distribution)
- Future work: DOEPOD upgrades
  - ➢ Interface with predicted POD MIL-HDBK-1823
    - companion tool
  - ➢ Address very limited data sets when 90/95 $X_{POD}$ can never be reached, and communicating those risks.




**edward.r.generazio@nasa.gov**

• **DOEPOD Probability of Hit estimating curve is for visualization only and not used in the DOEPOD analysis.**

• **Probability of Hit estimating curve is not to be used for validation or for justification of validation.**

• **The default function used in DOEPOD is:**

$$POH = Exp(a(1) + a(2) * Log(x1)) / (1 + Exp(a(1) + a(2) * Log(x1)))$$

$a(1) = \alpha$

$a(2) = \beta$

$x1 = Flaw\ size$

• **Other multi-parameter functions may be used**